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METHOD OF AUTONOMOUS GUIDANCE DURING FLIGHTS IN NEAR-PLANET ORBITS

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A method for autonomous navigation of a spacecraft, under full control of the astronauts, is described, based on practical experience of the Voskhod-2 flight. Conventional navigation methods are used on board the craft, taking fixes on two heavenly bodies preselected by the ground station before blast-off. The times t_1 and t_2 at which these bodies are at a predetermined altitude above the planet horizon and the period of revolution of the craft are used in computing the time of cut-in of the retro rockets for transfer to a parking orbit or for soft landing on the planet. author

During the flight of a spacecraft in a near-planet orbit, it may become necessary to solve the following major navigational problems:

Determination of the motion of the craft relative to the surface of the planet or to the fixed stars, so as to pre-assign the time of observation of various objects on the planet or in space;

Determination of the time and parameters for cutting in the propulsion system to correct the orbit;

Determination of the time and parameters for starting the retrorockets for landing the vehicle within a predetermined area of the planet under allowable g - loading conditions if the planet has an atmosphere ;

Determination of the time and parameters for starting the propulsion unit to transfer the ship to a different flight path.

To maximize the reliability and safety of flight, the astronauts must be /2 able to solve all these navigational problems independently without reference to the work of the terrestrial command and tracking system.

We will here consider a simple method of autonomous solution of navigational problems by the astronauts in flight on a near-planet orbit by taking astronavigational observations and measuring the flight altitude. In this, the astronauts must perform simple calculations with the aid of special navigation Tables. No computer devices need be carried on board.

A sextant-type navigation instrument may be used for the astrometric

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* Numbers in the margin indicate pagination in the original foreign text.

observations. Such instruments are simple and reliable, have satisfactory accuracy, and are light in weight. The spaceship must be provided with an altimeter to measure the flight altitude.

Let us assume that the orbit of the ship is almost circular and that its orbital plane does not differ greatly from nominal. The small eccentricity of such an orbit permits certain assumptions as well as the use of relations obtained by linearizing quasi-circular motion and the resultant consequences. The assumption that the plane of actual motion does not differ very greatly from the plane of the nominal is not essential and is merely to simplify the exposition, since the plane of motion can always be roughly determined by observations of the motion of the stars relative to the planet, and this roughly determined plane can then be adopted as the nominal plane. The pertaining formulas may be very simple. /3

To solve the problem of predicting the time of observation of various objects on the planet, it is sufficient to determine the actual motion of the ship in first approximation. In most cases the required accuracy of prediction is attained if it is assumed that the motion is in the nominal plane, and that the orbit is exactly circular. In this case, all that is needed to determine the motion is to find the period of revolution of the ship in orbit and the instant τ when the ship passes some fixed direction. These two quantities may be determined by the following method:

Some heavenly body close to the plane of motion is selected, and the time t_1 when it is at a certain altitude h above the horizon of the planet is determined by the aid of a navigation instrument. After one or n passes of the ship, the time t_2 when the same body is at the same altitude h is then determined. Both times t_1 and t_2 must correspond to the rising or setting of the body. The period of revolution is determined by the formula:

$$T = \frac{t_2 - t_1}{n}$$

The time t_1 or t_2 may be taken as the instant τ. Based on the measurements of the period of revolution and the time τ, the radius of the orbit and the velocity of the vehicle on this orbit can then be determined by the aid of Tables or graphs. Again on the basis of the corresponding Tables and graphs the motion of the spaceship may also be projected onto the surface of the rotating planet and the time of passage over the desired points of the path may be determined. From the flight altitude, the area of the visible region can be determined. /4

A more accurate knowledge of the actual motion is required to solve the other navigational problems.

The exact determination of the orbit is performed in two stages. First, the circular orbit closest to the actual one is determined. Then the corrections to this orbit are determined so as to reflect the difference between the actual motion and the circular orbit determined in first approximation.

It is assumed, in first approximation, that the motion takes place in some predetermined plane not greatly differing from the plane of nominal motion.

This plane will hereafter be termed the basic plane, while the normal to it will be denoted by the letter N. To determine the circular orbit it is necessary to measure the period of revolution $T_н$ and the instant of passage of some fixed direction τ. Determination of $T_н$ and τ proceeds by the method given above.

From the measured quantities $T_н$ and τ it is possible to find the radius of the circular orbit, the orbital velocity, and the angle included by the instantaneous position of the radius vector of the ship from the center of the planet and the predetermined fixed direction.

The corrections to the circular motion are determined from the results of the astrometric data and the measurements of the flight altitude, making use of relations obtained by linearization of the quasi-circular motion corresponding to the measured period $T_н$. The expressions for the corrections of the motion as a function of the time of flight t are of the form: /5

$$\left.\begin{aligned}
\Delta z &= 2 z_н \frac{\Delta T}{3 T_н} - \frac{1}{\lambda} A_n \sin[\lambda(t-t_2)+\psi_n];\\
\Delta U &= \Delta U_1 - \lambda \frac{\Delta T}{T_н}(t-t_3) + \frac{2 A_n}{V_н}\cos[\lambda(t-t_2)+\psi_n] - \frac{2\Delta V_{z_1}}{V_н};\\
\Delta V_z &= A_n \cos[\lambda(t-t_3)+\psi_n];\\
\Delta V_u &= -V_н \frac{\Delta T}{3 T_н} - A_n \sin[\lambda(t-t_3)+\psi_n];
\end{aligned}\right\} \quad (1)$$

$$\left.\begin{aligned}
z &= \frac{1}{\lambda} A_2 \sin[\lambda(t-t_1)+\psi_2];\\
V_z &= A_2 \cos[\lambda(t-t_1)+\psi_2],
\end{aligned}\right\} \quad (2)$$

where

$r_н$, $V_н$ = radius and velocity in the circular orbit about which linearization is performed;

U, $U_н$ = angle included by the radius vector of the ship position and the fixed direction in flight in the actual orbit and in the circular orbit;

r, V_r, V_u = radius vector, radial and transverse velocity components,

Z, V_z = angle between radius vector and base plane, and projection of the velocity onto the normal N;

r_p = radius of the planet;

$\lambda = \frac{2\pi}{T_н}$ = mean angular velocity of the ship in orbit.

The quantity $\Delta T = T - T_н = 0$, since T is the period of revolution on the actual orbit, equals the period of revolution in the orbit about which linearization is being performed.

The angles ψ_n and ψ_2 as well as the quantities A_n and A_2 are determined by the formulas:

$$
\left.
\begin{aligned}
\sin\psi_n &= -\frac{1}{A_n}\left(\lambda\,\Delta z_1 + 2\,\Delta V_{u_1}\right) \\
\cos\psi_n &= \frac{1}{A_n}\,\Delta V_{z_1} \\
\sin\psi_2 &= \frac{1}{A_2}\,z_1\,\lambda \\
\cos\psi_2 &= \frac{1}{A_2}\,V_{z_1} \\
A_n &= \sqrt{\Delta V_{z_1}^2 + \left(\lambda\,\Delta z_1 + 2\,\Delta V_{u_1}\right)^2} \\
A_2 &= \sqrt{(z_1\lambda)^2 + V_{z_1}^2}
\end{aligned}
\right\} \qquad (3)
$$

The index 1 denotes parameters relating to the [illegible]

The corrections to the circular orbit may be determined by two methods. The first method uses only measurements of the altitudes of the navigational heavenly bodies above the horizon of the planet, while the second also uses astronavigational observations and measurements of the flight altitude by the on-board altimeter. Only the second method will be considered here. The principle of the first method is similar, and the required relations may be derived without trouble in the same way as those for the second method. The first method, however, requires the astronauts to perform a somewhat greater number of calculations and is also somewhat less accurate.

The proposed method is as follows: The flight altitude H_1 is measured at a certain instant of time t_3. Then, at the time $t_4 = t_3 + \frac{T}{4}$, the flight altitude H_2 is measured. From these measured values of the flight altitude, the corrections to the orbit at the instants of time t_1 or t_2 may be found. In fact, the relations of the system of equations (1) will yield:

$$
\left.
\begin{aligned}
\Delta z_1 &= \left[z_{p_1} + H_1 - z_H\right] \\
\Delta V_{z_1} &= \lambda\left[z_{p_2} + H_2 - z_H\right] \\
\Delta V_{u_1} &= \lambda\left[z_{p_1} + H_1 - z_H\right]
\end{aligned}
\right\} \qquad (4)
$$

where r_{p_1} and r_{p_2} represent the radius of the planet at the point of measurement of H_1 and H_2, respectively.

These quantities permit a determination of the quantities A_2 and ψ_2 on the basis of eqs.(3) or by the aid of the corresponding Tables. Knowing the latter quantities, it then becomes possible for the astronauts, by using still other Tables and by applying the formulas of the system (1), to derive the corrections to the orbit at any other time. The deviation from circular motion along the path is determined by the second relation of the system of equations (1). To decrease the number of navigational fixes, it is advisable to take the instant of time t_3 to be the same as the instant τ. Then,

$$\Delta l_1 = \Delta U_1 Z_u = 0 ,$$

$$\Delta l = \frac{2}{\lambda}(\Delta V_{z_1} - \Delta V_z).$$

The position of the actual orbital plane relative to the basic plane can be determined by the formulas of the system (2), if the values of the angle Z are determined at two points of the orbit, spaced by 90°. Actually, on the basis of the formulas in the system (2), we find that

if at the time $t = t_1 \qquad Z = Z_1$,

then, at the time $t = t_2 = t_1 + \frac{T}{4} \qquad Z = Z_2 = \frac{1}{\lambda Z_u} V_{z_1}$,

whence it is readily possible to find the values of Z_1 and V_{z_1} corresponding /8 to the same instant of time t_1. From the values of Z_1 and V_{z_1}, we can calculate the values of A_2 and ψ_2 by means of eqs.(3) or of Tables prepared in advance, while the deviations Z and V_z at any other instant of time can be calculated from eqs.(2).

The angles Z_1 and Z_2 can be determined by the astronauts by measuring, at the instants of time t_1 and t_2, the altitude of a given heavenly body on the normal N to the base plane. The deviations Z are calculated by the obvious formula (see Fig.1):

$$Z = \frac{\pi}{2} - \gamma ,$$

where γ is the zenith distance of the heavenly body. In turn, γ may be determined from the formula (see Fig.2)

$$\gamma = \frac{\pi}{2} + \beta - h ,$$

where β is the depression of the horizon due to the flight altitude H, and h is the measured altitude of the heavenly body above the horizon.

Observations of a body located on the normal N ensure maximum simplicity and accuracy of determination of the angles Z. It is therefore rational to select the base plane such that the normal N points exactly to some star of sufficient brightness. In this case, however, the base plane must not deviate

substantially from the plane of the nominal orbit.

From the values found for Z_1 and V_{z_1} the inclination of the orbit to the base plane and the position of the ascending node may be found.

The accuracy of determination of the orbit by the proposed method was evaluated for the flight of a ship on a selenocentric orbit in a plane close to the lunar equatorial plane. The factors considered were the effect of errors in measuring the altitudes of the heavenly body above the horizon, errors in measuring the flight altitude, inaccurate knowledge of the distances from the surface to the center of the moon at the sites of measurement, error in the gravitational constant μ of the moon, etc. It was assumed, in making the evaluation, that the periodic perturbations of the flight altitude due to the Earth's influence had been taken into account in eqs.(4) by applying a correction depending on the angle between the radius vector of the ship at the instant of measurement and the direction to the Earth. The value of this angle must be known at least approximately. Tables may be prepared in advance to facilitate the work of the astronaut in finding the required quantities. /9

An analysis of the effect of various errors showed that the principal error in determining the parameters of motion is due to the inadequate knowledge of the distance r_p from the center of the moon to its surface in the range of the point of measurement. Since the measurements for determination of the orbit may be made over regions of plains selected in advance, the inadequacy or error in our knowledge of the value of r_p may be minimized by using the proposed method. If this error is assumed to be $|\delta r_p|_{max} \approx 0.5$ km, then, as shown by the computational data, the parameters of motion may be determined with the following errors: /10

$$|\delta z|_{max} \approx 0.8 \text{ km} \qquad |\delta V_z|_{max} \approx 0.5 \text{ m/sec}$$

$$\text{km} \qquad |\delta V_u|_{max} \approx 0.5 \text{ m/sec}$$

$$|\delta \ell|_{max} = z_u |\delta \dot{z}|_{max} \approx 1.5 \text{ km} \qquad |\delta \ell|_{max} \approx 4.5 \qquad |\delta V_z|_{max} \approx 1 \text{ sec}$$

If the error δr_p proves greater than assumed, then the determination errors of the parameters of motion will increase approximately in direct proportion with the error δr_p.

From the obtained parameters of motion, it is possible to determine all characteristics required for starting the propulsion system of the vehicle for any desired maneuver. Tables or charts may be prepared for finding these characteristics. /11

For maneuvers in space whose ultimate objective can be exactly determined on Earth in advance of launching, it is possible to devise a technique for determining the parameters of engine cut-in directly from the results of the navigational data, without the intermediate step of determining the flight path. As an example, let us briefly consider the method of finding the time of firing the retro rockets to prepare for a landing on the planet surface, for which the descending path of landing must be as constant as possible. Let us assume that

the actual orbit differs only little from the nominal orbit known in advance. This assumption permits the use of the linear theory. Let us assume likewise that the required flying range is ensured by a suitable selection of the instant of starting the propulsion unit and that the magnitude of the braking impulse and its direction are known functions of the time of engine cut-in.

To solve the problem, two celestial bodies for taking fixes are selected in advance at the ground station. During flight, the astronauts observe these bodies and determine the instants of time t_1 and t_2 when these bodies are at some predetermined altitude above the horizon of the planet. The astronauts must also determine the period of revolution of their space vehicle by the technique given above. Then, from the value of the difference $t_2 - t_1$ and the period of revolution T, using Tables prepared in advance, the navigator determines the time that must elapse after t_2 before the propulsion unit must be started in order to make descending phase approximately constant. The position of the celestial bodies relative to the plane of the nominal orbit, and the /12 altitudes of those bodies when t_1 and t_2 are determined, may be selected on the basis of the condition that the probable deviations of the descending flight range from the required value shall be minimum. The method considered is simple and of satisfactory accuracy.

Until recently, there were no experimental data available on the possibilities and conditions of solution of navigation problems by astronauts in actual flight. The first such data were obtained from the navigation experiments performed by K.P.Feoktistov, during the recent flight of the "Voskhod". His tasks included:

To study the difficulty of recognizing the constellations and the individual stars in observations from the capsule of the vehicle during space flight.

To evaluate the sharpness of the visible line of the horizon and the possibility of distinguishing it from clouds and mountains.

To determine the possibility of navigational observations of celestial bodies on the night side of the Earth,with the moon surface illuminated and with the surface in shadow.

To evaluate the convenience of working with the navigation aids such as sextants etc. under flight conditions.

The results of these experiments, in brief, were as follows:

1. There was no particular trouble in recognizing the constellations and individual stars from the spaceship cabin under flight conditions, as compared with terrestrial conditions. He observed and identified many constellations and individual stars of the Northern and Southern hemispheres, including even faint and uncharacteristic constellations and stars. /13

2. The distinctness of the horizon varies during flight. Sometimes it is fairly distinct and at other times it is very blurred. Visual observations as well as the interpretation of black-and-white and color photographs of the

horizon on the day side of the Earth, showed the mean error of determination of the horizon to be of the order of 2'. However, it proved rather difficult to determine the physical level to which the visible horizon corresponded. This level could be the upper boundary of the clouds or else the top of the troposphere, etc. Feoktistov observed no clearly identifiable mountains or clouds on the horizon.

3. The horizon was readily identified on the night side by the light of the moon. Above the horizon, in moonlight, the astronaut observed additional brightness strata due to the glow of the upper atmosphere. An astronaut, however, would be most unlikely to confuse the boundary of these strata with the horizon. In the absence of moonlight, it is difficult to identify the horizon on the night side, and navigational fixes become highly complicated.

4. It is entirely possible to measure the heights of the stars above the horizon. Feoktistov made a number of suggestions on the instrument design and on the need for modifying certain parts in order to more fully adapt the device to the conditions of space flight.

During the flight of the Voskhod-2, the ship commander, P.I.Belyayev, also took observations to clarify certain aspects of space navigation. He was the first person to solve navigation problems under space flight conditions. /14

His results, in brief, were as follows:

1. He confirmed the fact that there is no particular difficulty in identifying the constellations and individual stars under the conditions of space flight as compared with the conditions of orientation on the ground or from an aircraft in flight.

2. His observations, like those by Feoktistov, showed that the horizon is plainly recognizable at some instants, but that in flight over other regions there is a rather smooth transition from the Earth's surface to the atmosphere. As in the Feoktistov observations, he had difficulty in identifying the visible horizon with the edge of the Earth, with the upper boundary of the atmosphere, etc. To refine this item further, corresponding investigations will have to be made on manned satellites. It may well be that observations of the horizon in infrared or ultraviolet light will prove useful. The moonlit horizon was rather easy to distinguish - the moon having been almost full during the flight of the Voskhod-2.

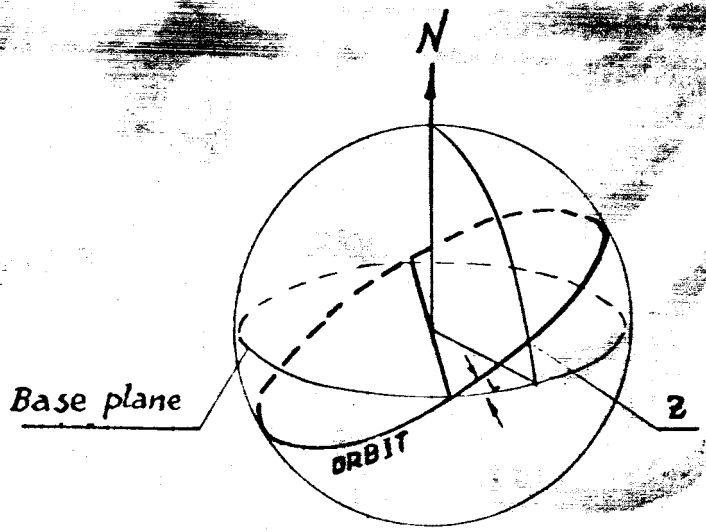
Both Belyayev and A.A.Leonov observed additional brightness strata. These strata, however, did not interfere with identification of the horizon.

3. During the flight, Belyayev solved several navigation problems. In particular, by measuring the height of the Moon above the horizon with a special sextant, he determined the period of revolution of the ship in orbit. He also made navigational observations permitting an approximate construction of the projection, onto the Earth's surface, of the actual motion of the ship and the calculation of the time of passage of individual points on that orbit. /15

A characteristic feature of the Belyayev experiments was that his navigational determinations were made under various stabilization conditions of the space vehicle.

As a result, it can now be considered established that navigational determinations can be made even in non-oriented flight, with preliminary damping of high angular velocities.

The results of the observations and experiments by Feoktistov and Belyayev permit the assertion, with complete confidence, that autonomous navigation of spaceships is entirely possible. In the not-too-distant future, complete familiarity with these methods by all spaceship crews will become routine requirement.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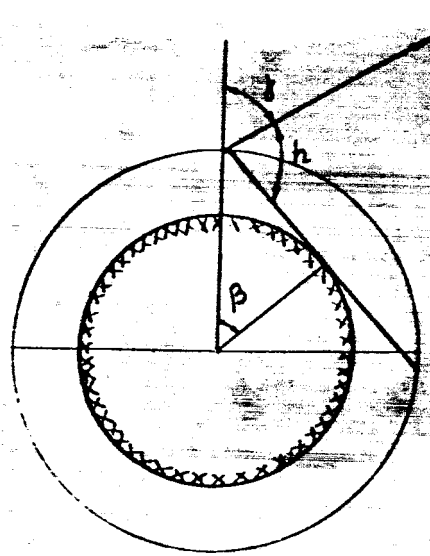
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Fig.1

Fig.2